Reliable Query Reporting

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Motivation

- Effective communication among sensors necessary for collaborative tasking

- Major issues in sensor communication
  - Sensor Failure
  - Costs of Communication

Reliable Query Reporting (RQR)

Optimization Problem: Given that sensors may be faulty and costs of communication vary, how do we design self-configuring and adaptive sensor networks that can reliably route event information from observing sensors to querying nodes taking communication costs into account?

RQR: Complementary in Nature

- Research on Data Fusion/CSP/Distributed Computing aspects of sensors networks often does not focus on reliable communication aspects.
- Communication rules based on ad-hoc routing/data fusion optimizations do not provide general bounds on reliable energy constrained communication.

Vision

- Goal: To *develop* a rigorous analytical framework for solving the RQR problem
- Technique: Game Theory
- *Complement* existing projects in SenseIT on energy efficient routing, tasking and sensor deployment.

Game-Theoretic Framework

- Each sensor makes decisions taking individual costs and benefits into account
  - Decentralized decision-making
  - Self-configuring and adaptive networks
  - Allows us to identify equilibrium outcomes for reliable communication and their stability and uniqueness properties
- This framework allows us to design communication rules for sensor networks

RQR Model Setup: *Self-configuring Phase*

- Set of players: $S = \{s_a = s_1, \ldots, s_N = s_q\}$.
- Source node (s_a) wants to send information V_a to destination node (s_q).
- Information routed through optimally chosen set $S' \subseteq S$ of intermediate nodes
- Each node can fail with probability $1\text{-}p_i \in (0,1)$.
- Normalized link costs $c_{ij} > 0$.
- Each node forms one link.

Components of RQR Game

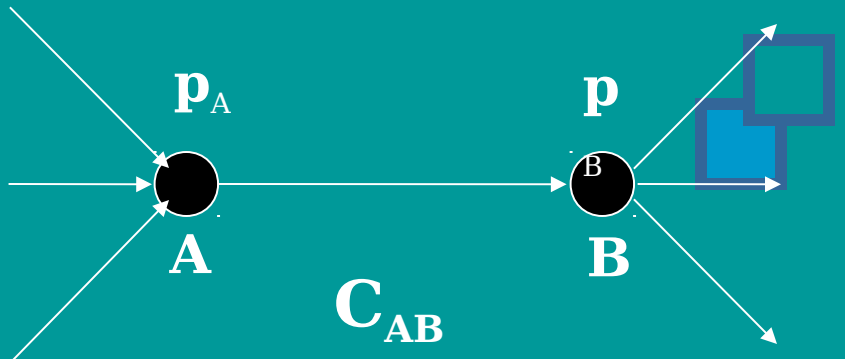
- Sensor s_i's strategy is a binary vector $l_i \in L_i = (l_{i1}, \ldots, l_{ii-1}, l_{ii+1}, \ldots, l_{in})$.
- A strategy profile $l = (l_1, \ldots l_n) \in \times_{i=1}^{n} L_i$

defines the outcome of the RQR game.

- Modeling Challenge: In a standard non-cooperative game each player cares only about individual payoffs – therefore behavior is *selfish*.

Information and Payoffs

- Information at B: $V_b = p_a V_a$
- Expected Benefit of A: $p_b V_a$
- Payoff of A: $\Pi_a = p_b V_a - c_{ab}$



RQR Payoff Models

- General Payoff Function:

$$\Pi_i = f_i(R) g_i(V_a) - c_{ij}$$

where $ij \in S \times S$ and R is path reliability.

- Payoff of all sensors not on the optimal path is zero.

Payoff Models

- Model I: Probabilistic Value Transfer

$$f_i(R) = \prod_{t=i+1}^{q} p_t, \quad g_i(V_a) = V_a \prod_{t=a}^{i} p_t$$

- Model II: Deterministic Value Transfer

$$f_i(R) = \prod_{t=i+1}^{q} p_t, \qquad g_i(V_a) = V_a$$

- Model III: Probabilistic Under Information Decay

$$f_i(R) = \prod_{t=i+1}^{q} p_t, \qquad g_i(V_a) = \delta^k V_a \prod_{t=a}^{i} p_t$$

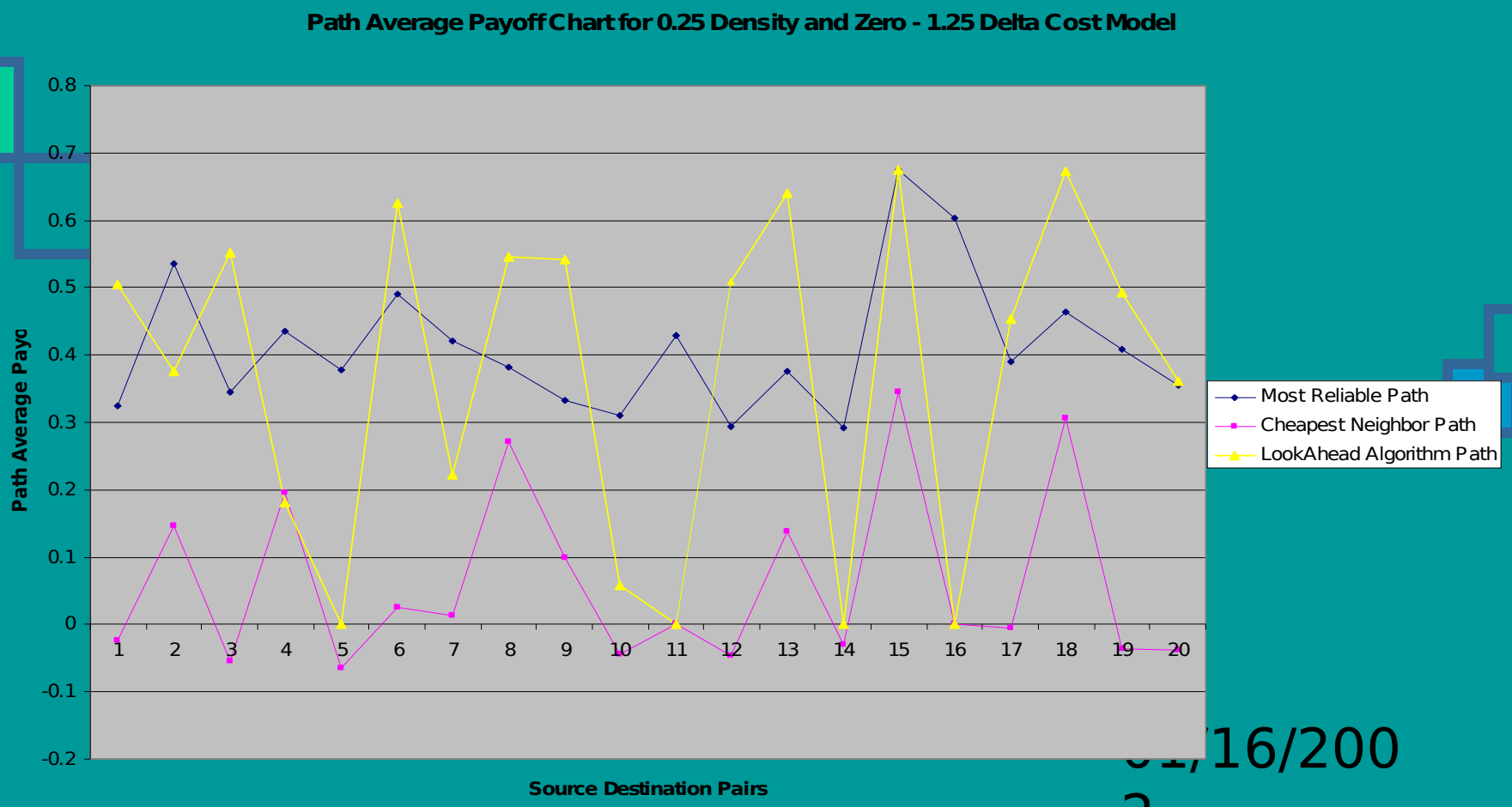
Model Properties

- Benefits depend on the *total reliability* of realized paths. Thus each sensor is induced to have a cooperative outlook in the game.
- Costs are *individually borne* and differ across sensors, thereby capturing the tradeoffs between reliability and costs.
- **Careful choice of payoffs captures the interplay between global network reliability and individual sensor costs.**

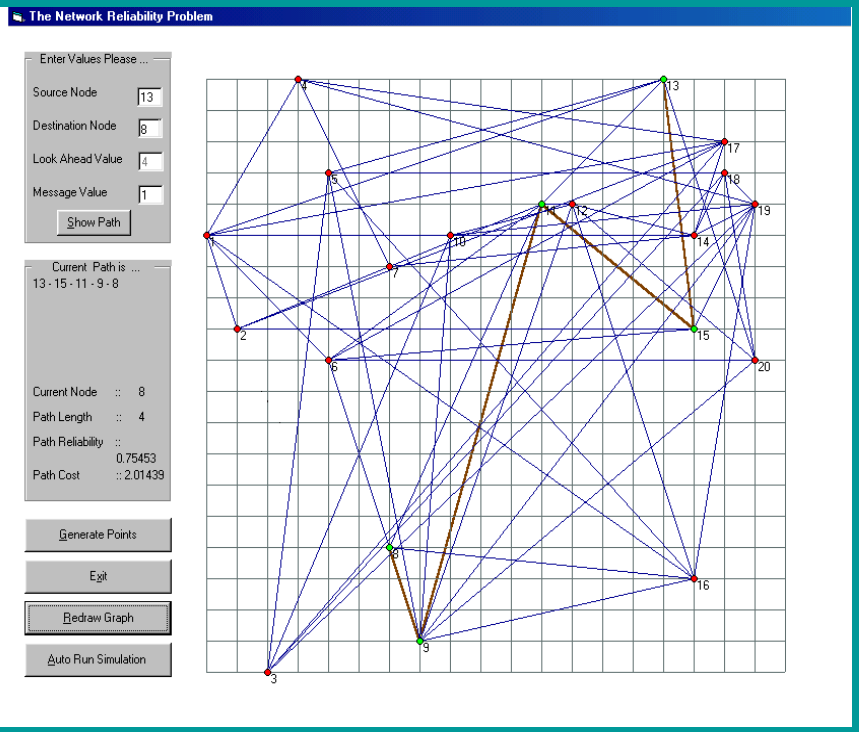
Equilibrium Properties

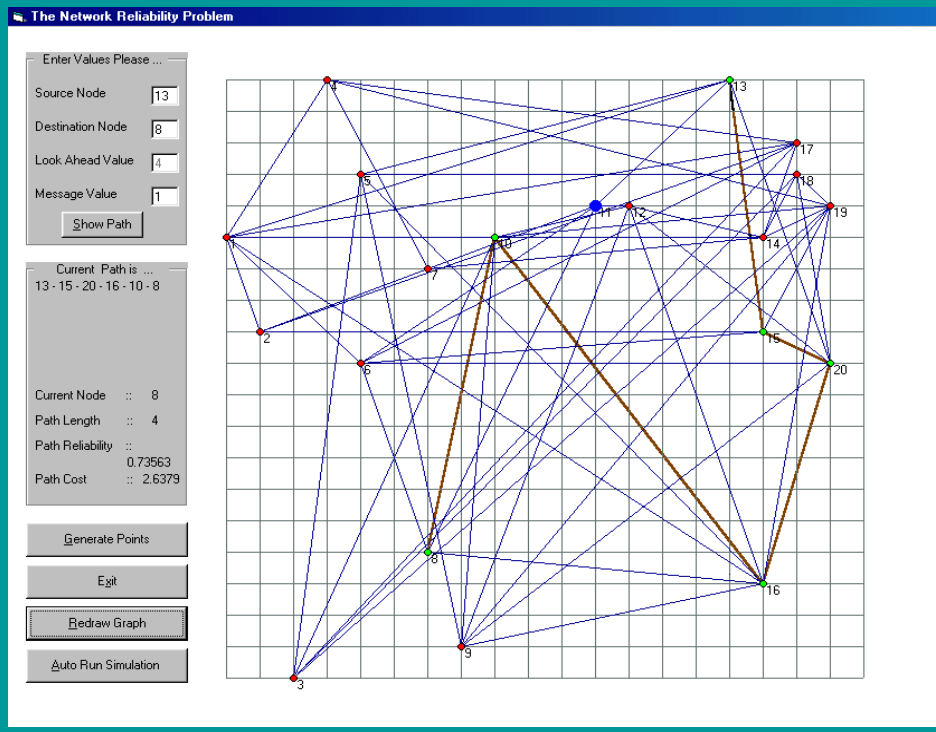
- Nash Equilibrium: The outcome where each sensor plays its *best response*.
- It defines the *optimal* RQR path!
- Stability Property: An individual sensor cannot increase its payoffs by *unilateral deviation*.
- The sensor network is self-configuring.

Optimization Criteria and Payoffs



Transition to Adaptive Networks





Repeated Self Configuring RQR Games

Complexity Results

- Theorem: All variations of the RQR path problem are *NP*-Hard given arbitrary sensor success probabilities $\{p_i\}$ and costs $\{c_{ij}\}$.
- This includes computing the optimal path under all three payoff models even with uniform success probabilities.

Performance Metrics for Results

- Most Reliable Path
- Cheapest Neighbor Path
- Overall Cheapest Path
- Optimal Path

Results

The following results hold for sensors deployed in any arbitrary topology:

- Given $p_i \in (0,1)$ and uniform $c_{ij} = c, \forall ij$, the optimal path is also the most reliable path.
- Given uniform sensor failure probabilities, the optimal path will be most reliable if

$$c_{\max} - c_{\min} < p^{m-1}(1-p)$$

$\forall s_i$ on the shortest path.

Results

- Given non-uniform success probabilities $\{p_i\}$ and costs $\{c_{ij}\}$ the optimal path will be most reliable if

$$\frac{\Delta C_{i+1}}{\Delta C_i} < \frac{\Delta R_{i+1}}{\Delta R_i}$$

$\forall s_i$ on the shortest path.

Results

- Given uniform $p_i = p$, the cheapest neighbor path will be optimal if

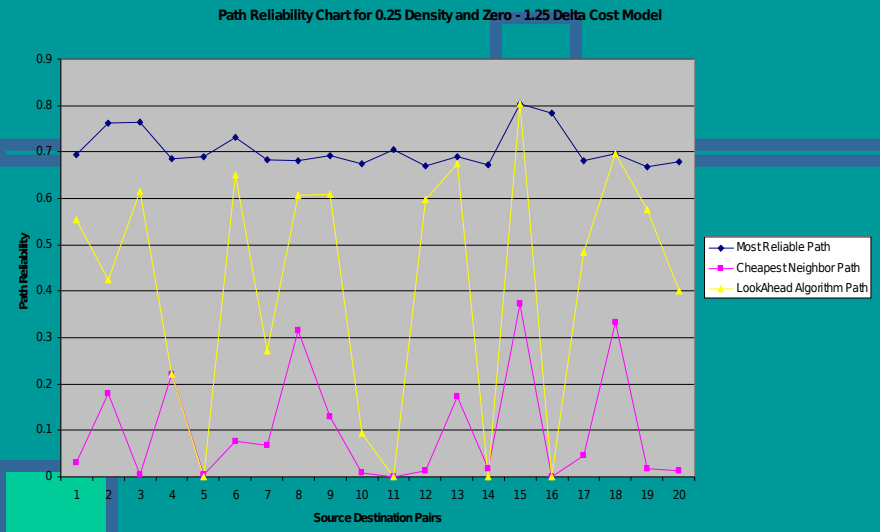
$$\min\{C^i \setminus C^i_{\min}\} - C^i_{\min} > p^2(1 - p^{l-2})$$

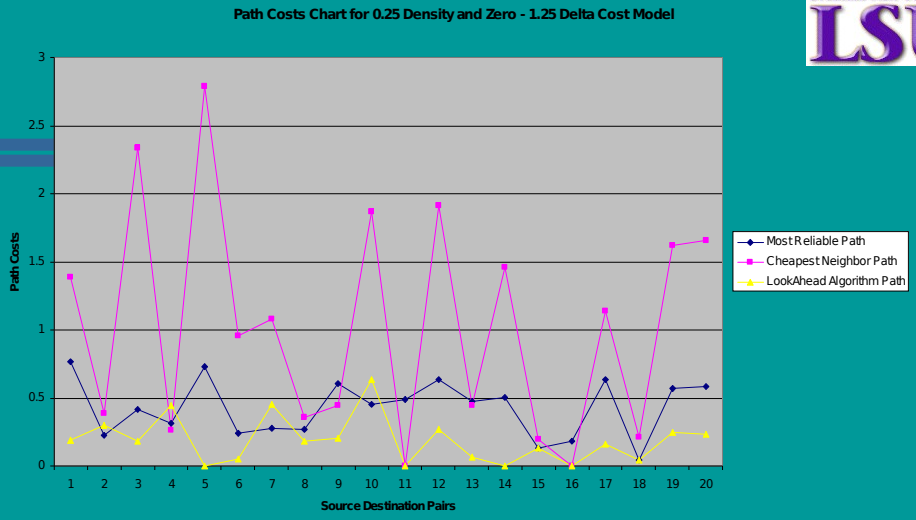
Sensor Density and Payoffs

- What is the number of sensors that need to be deployed to guarantee a threshold level of reliability for the optimal RQR path?
- Ties-in with existing SenseIT projects on sensor deployment strategies.

Heuristics: *k*-Look Ahead

- Each sensor computes its next neighbor based on *k*-hop reliability information.
- *Intuition*: As sensors look further ahead in the network decision-making becomes less myopic.
- Advantages
  - Limits number of computations.
  - Reflects limited neighborhood information.
  - Limits flooding overhead.


Path Reliability Chart for 0.25 Density and Zero - 1.25 Delta Cost Model
Path Reliability
Source Destination Pairs
Most Reliable Path
Cheapest Neighbor Path
LookAhead Algorithm Path


Path Costs Chart for 0.25 Density and Zero - 1.25 Delta Cost Model
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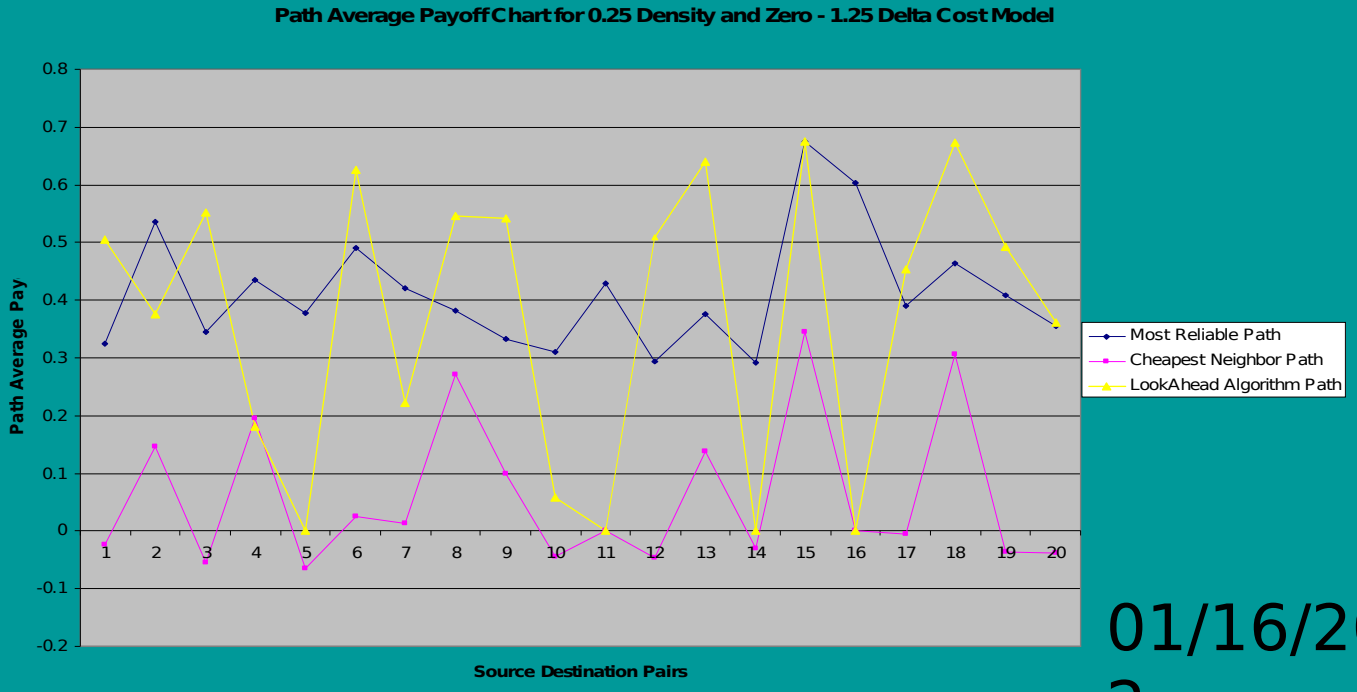
Path Average Payoff Chart for 0.25 Density and Zero - 1.25 Delta Cost Model
Path Average Pay
Source Destination Pairs
Most Reliable Path
Cheapest Neighbor Path
LookAhead Algorithm Path

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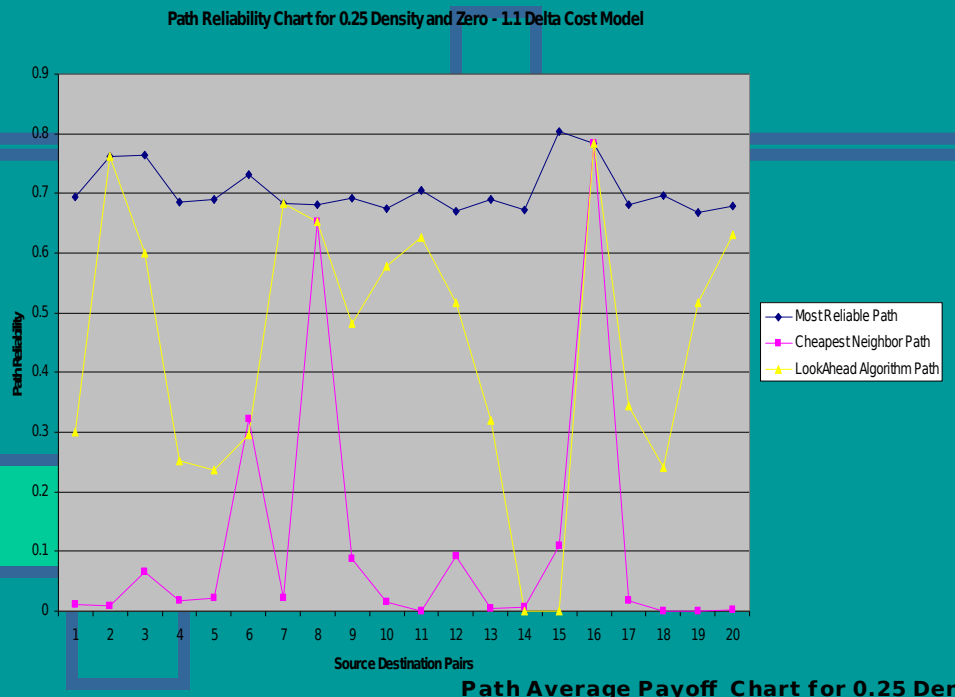
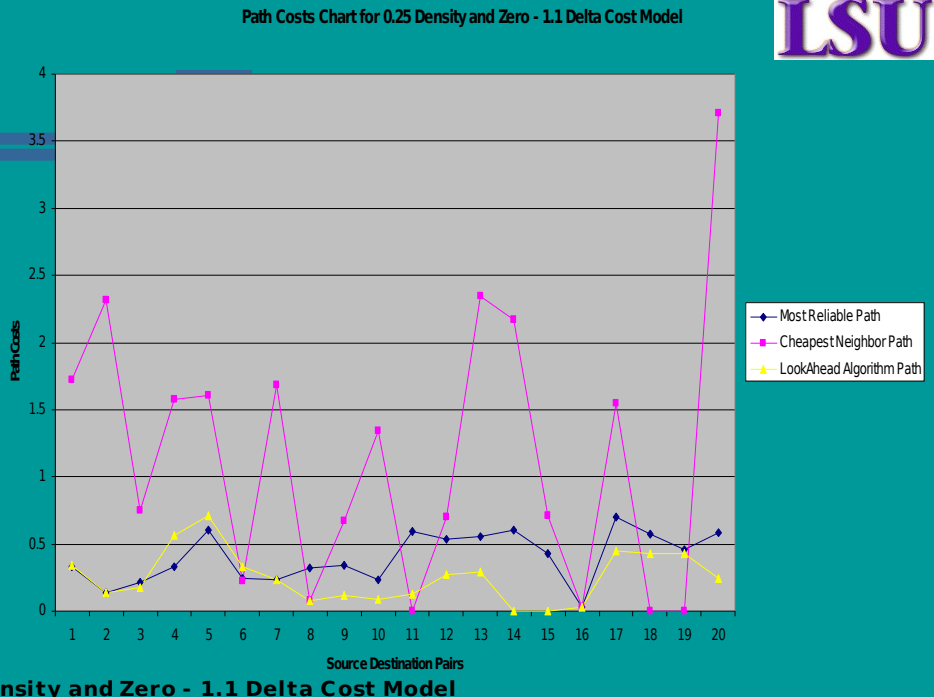

Path Reliability Chart for 0.25 Density and Zero - 1.1 Delta Cost Model
Path Reliability
Source Destination Pairs
Most Reliable Path
Cheapest Neighbor Path
LookAhead Algorithm Path


Path Costs Chart for 0.25 Density and Zero - 1.1 Delta Cost Model
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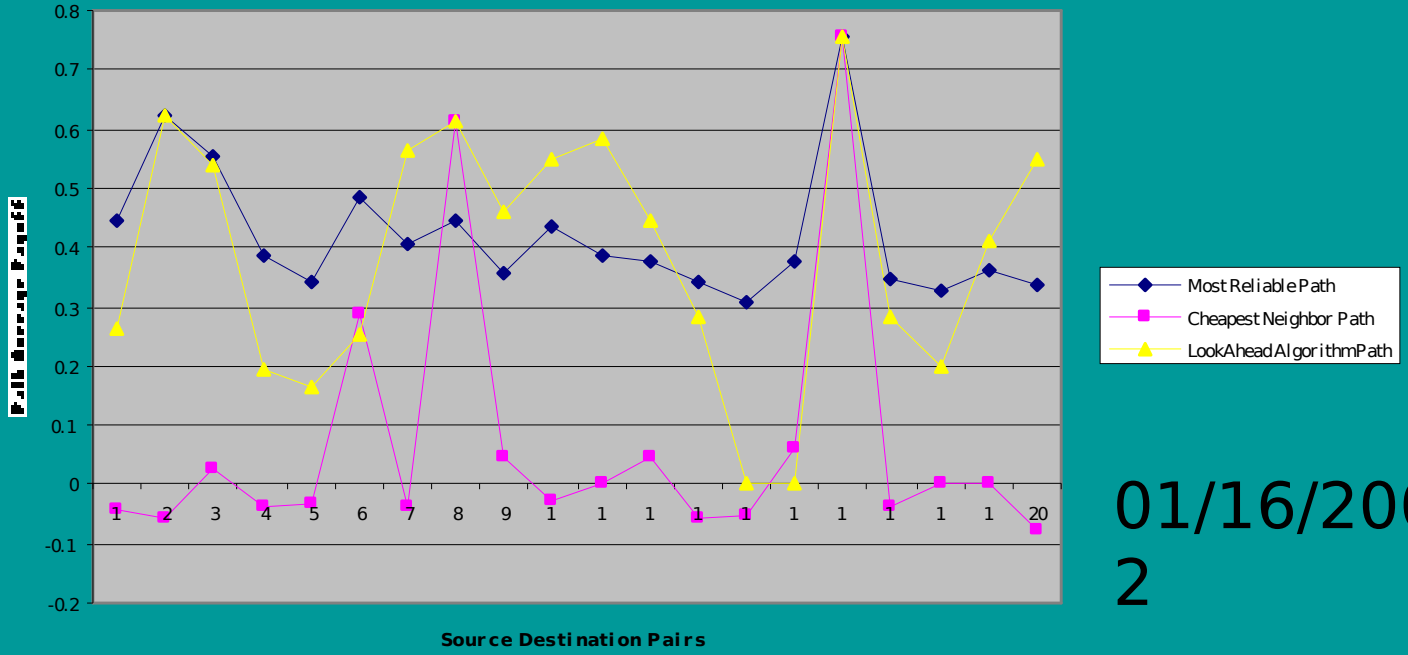
Path Average Payoff Chart for 0.25 Density and Zero - 1.1 Delta Cost Model



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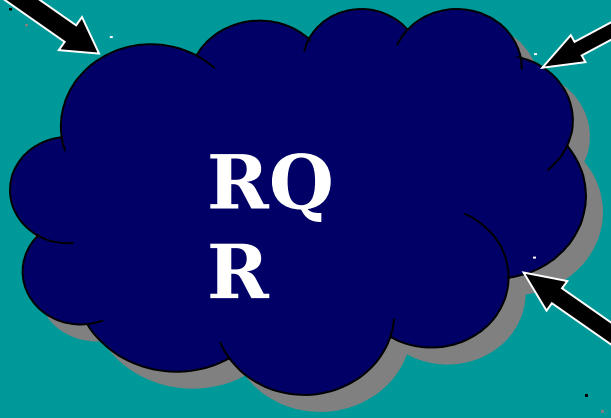
RQR Synergies

Sensor Deployment
- Link Cost
- Node Failure

Communication for Data Fusion
- Data Fusion
- Reliable Clusters



Energy Constrained Routing
- Payoff Implication

Accomplishments

- Developed a theoretical framework.
- Developed a user friendly simulation program for solving game-theoretic network optimization problems.
- Submissions: Journals (2), Conferences (1).

Look Ahead

- Bounds on Approximability and Approximation Algorithms
- Multiple Links
- Value Aggregation
- Structured Graph Topologies: Clusters and Hierarchies
- Dynamic and Adaptive Networks